



Influence of climatic conditions and control logic on NO_x and CO emissions of a micro-cogeneration unit serving an Italian residential building



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HIGHLIGHTS

- Local emissions of micro-cogeneration system were evaluated.
- Influence of climatic conditions and control logic was investigated.
- The micro-cogeneration system was compared with a conventional system.
- The micro-cogeneration system reduces the NO_x emissions.
- The micro-cogeneration system increases the CO emissions.

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ABSTRACT

The increasing diffusion of micro-cogeneration systems is raising the need for studying their environmental impact in order to assess their sustainability. The adoption of the systems for the combined production of heat and power may provide a significant reduction of global impact in terms of carbon dioxide emissions with respect to the separate production of electricity and heat. However, a comprehensive environmental evaluation of this technology should take into account as well the impact due to the presence of plants spread over the territory that could increase the local pollution, in particular due to nitrogen oxides and carbon monoxide, and thus could worsen the local air quality.

In this paper the nitrogen oxides and carbon monoxide emissions of a residential building-integrated micro-cogeneration system were evaluated; a 6.0 kW_{el} natural gas fuelled internal combustion engine-based micro-cogeneration unit was coupled with a multi-family house compliant with the transmittance values suggested by the Italian Law. The analyses were carried out by using the whole building simulation software TRNSYS upon varying the city where the building is located (four Italian cities representative of different climatic regions were considered) as well as the control logic of cogeneration device (electric and thermal load-following strategies). The simulated performance of the proposed system was compared with those of a conventional system composed of a natural gas-fired boiler (for thermal energy production) and a power plant mix connected to the central electric grid (for electricity production) in order to assess the suitability of the cogeneration-based system in reducing the local emissions.

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1. Introduction

Micro-cogeneration (MCHP) is the combined production of heat and power with electric output lower than 50 kW_{el} [1]. The heat produced is used for space and water heating and possibly for

cooling, while the electricity is used within the building or fed into the grid [2,3]. The “core” of MCHP systems is a prime mover based on different technologies: reciprocating internal combustion engine (ICE), reciprocating external combustion Stirling engine (SE), micro-turbine (MT), and fuel cell (FC); among the others technologies, reciprocating internal combustion engine-based micro-cogeneration systems are usually the best choice for small scale cogeneration applications thanks to their robust nature and reliability, high thermal efficiency, fuel flexibility, reduced pollutant emissions, low noise and vibration, small installation space [2,3].

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In the last decade, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for distributed generation [4]. At present, environmental policies or concerns are probably the major driving force for the demand of distributed generation in Europe with a number of research programmes around the world, aimed at improving the performance of small-scale energy systems, as well as reducing the related emissions [5].

Several studies demonstrated the effectiveness of MCHP systems in reducing the primary energy consumption with respect to the conventional separate production of heat and electricity with a percentage difference varying from 10% to 30%, depending on the size and efficiency of the cogeneration units [5–7]. The reduction in the fuel consumption from such MCHP systems brings a corresponding reduction of global emissions of CO₂ in a first approximation similar to the amount of energy saving [8–10]. However, whilst basically all CHP plants provide primary energy saving with respect to the heat-and-electricity separate production, and thus potential CO₂ emission reduction at a global level, the scenario may be not so good for what concerns the local emissions [11,12]. In fact the diffusion of distributed cogeneration within urban areas, where air quality standards are quite stringent, brings environmental concerns on a local level due to the emission of hazardous air pollutants such as NO_x, CO, SO_x, particulate matter, unburned hydrocarbons, and so on. Indeed, in urban contexts dispersion in the atmosphere of pollutants from small-scale generators sited among buildings may be more difficult than, for instance, for large-scale power plants with high stacks. In addition, also due to the high population density, there is a number of relative weak receptors (elderly and sick people, children, etc.), with other potential impacts of pollutant emissions referred to ecosystems, monuments, and so forth. A further critical point is represented by the already high background emission level mostly due to road traffic pollution. As a consequence, air quality standards and emission limits can be quite stringent in urban areas, and the local impact of MCHP systems over the environment is an issue to analyse with care; therefore a comprehensive evaluation of micro-cogeneration systems should not consider the global environmental impact due to the CO₂ emissions only, but it should also take into account the local environmental impact associated to the presence of plants spread over the territory that could increase the local pollution, and thus could worsen the local air quality.

The most relevant hazardous pollutants emitted by natural gas-fired equipments are CO and NO_x (often subject to binding environmental constraints [13]). NO_x formation is the one giving most concerns from a regulatory point of view, being its toxic effects turning up for concentrations 10–20 times lower than for CO [13]. Subsequently, NO_x reduction represents also a research field in which several efforts have been put over the last years [14].

At the moment few works are available in literature concerning the evaluation of the local impact associated to cogeneration systems. Canova et al. [11] characterized both a 60 kW_{el} micro-turbine and a 180 kW_{el} internal combustion engine fed with natural gas in terms of air pollutants (in particular, NO_x, CO and non-methane organic compounds). The results from the case study showed that in general the micro-turbine always performs better than the internal combustion engine in terms of NO_x (but when it is operated at partial load the CO levels increase dramatically), while the CO emissions from the ICE are only negligibly affected by the engine load. Mancarella and Chicco [12] presented a general methodology to assess the emission impact due to adoption of MCHP systems in urban areas under general operating conditions (including, in particular, partial-load operation). They applied this methodology by considering two different MTs available on the market (with 30 and 60 kW_{el} as nominal electric output, respectively) fuelled with

natural gas. Their analyses highlighted how the full-load emission characterization can be unsuitable to estimate the environmental impact due to actual operating conditions; critical situations have emerged in the specific case for what concerns high NO_x emissions at low load (for the 30 kW_{el} MT) and high CO emissions mainly at medium-low loading condition. Pehnt [15] investigated the potential environmental effects of a deployment of micro-cogeneration on different levels. He noticed that whereas for fuel cells and Stirling engines emissions of air pollutants are extremely low, reciprocating engines emit more significant amounts of NO_x, CO, and hydrocarbons. Furthermore, the emission factors of reciprocating engines depend heavily on operation characteristics, age and maintenance of the systems. In addition to investigating the emissions side, analysis of the concentration of pollutants in a residential area supplied by reciprocating engines was carried out: the analysis showed that for selected, rather unfavourable, meteorological conditions, with a flat topography and urban housing structure, the additional level of NO_x due to the engines does not create severe additional environmental impacts. In a previous work [16] the authors estimated the NO_x and CO emissions of a residential building-integrated micro-cogeneration system during the winter. A commercially available 6.0 kW_{el} internal combustion engine based-MCHP unit fuelled with natural gas [17] was used to satisfy both thermal and electric requirements of a multi-family house composed of three floors compliant with the transmittance values of both walls and windows suggested by the Italian Law [18]. The whole system was analysed by means of the dynamic whole-building simulation software TRNSYS [19] (1 min simulation time step was used) in the case of the building located in the city of Naples (south of Italy) with the MCHP device operating under thermal load-following logic. In the current work the evaluation was extended in a wider range of operating conditions. In particular, in order to evaluate the influence of climatic conditions on the system environmental performance, a comprehensive sensitivity analysis was performed by considering the building located into four Italian cities representative of different climatic regions:

- Palermo (latitude: 38° 07' North; longitude: 13° 20' East);
- Napoli (latitude: 40° 50' North; longitude: 14° 15' East);
- Roma (latitude: 41° 53' North; longitude: 12° 29' East);
- Milano (latitude: 45° 28' North; longitude: 9° 10' East).

In addition to the thermal load-following logic, the operation of the MCHP unit under electric load-control strategy was also investigated with the main aim to assess the influence of the MCHP control logic on the local environmental impact.

The emissions of NO_x and CO calculated for the proposed system were compared with those of a conventional system composed of a natural gas-fired boiler (for thermal energy production) and a power plant mix connected to the national central grid (for electricity production) in order to assess the suitability of the MCHP unit based-system in comparison to the one based on separate energy production from an environmental point of view.

The analyses performed in Refs. [11,12,15] were performed by considering data on local emissions provided by the manufacturers, while in this paper the local emissions of the MCHP unit were calculated on the basis of the data measured at both the Advanced Engine Technology Ltd. in Ottawa (Canada) and the Canadian Centre for Housing Technology twin research homes [20] during full and part-load operation of the above-mentioned MCHP device [17]. Taking into consideration that often little attention is paid to the emission worsening that could be brought by consistent operation of micro-cogeneration devices at partial loads (this could lead to biased environmental assessment of the systems evaluated only on the basis of the full-load performance, whereas load-tracking

operation can frequently occur), in this paper the part-load characteristics of the cogeneration unit was fully considered by using a detailed dynamic model [21,22] calibrated and validated by the authors based on experimental results [23,24]. The local emissions associated to both the boiler and central electric grid were calculated by using the standard emission factors approach suggested in Ref. [12].

In Sections 2 and 3 the proposed system is described in detail, while Section 4 provides the main characteristics of the system assumed as reference. The applied methodology and the main results obtained from the simulations are reported and commented in the Section 5.

2. Description of the proposed system

Fig. 1 shows the scheme of the system configuration analysed in this study. The whole plant basically consists of a micro-cogeneration device (MCHP), an auxiliary boiler (BOILER), a combined storage tank (TANK) with three internal heat exchangers (IHE1, IHE2, IHE3), a plate-fin heat exchanger (PHE), three pumps (P1, P2, P3), three thermostats (T1, T2, T3), two 3-way valves (V1, V2), two flow diverters (D1, D2), and a group of fan-coils installed within the building.

Four different main circuits can be easily distinguished in Fig. 1:

- 1) micro-cogeneration device circuit;
- 2) natural gas-fired boiler circuit;
- 3) space heating circuit;
- 4) domestic hot water circuit.

Both natural gas and electricity lines are also highlighted in Fig. 1.

The system under investigation is devoted to satisfy the space heating sensible load, the domestic hot water requirements and the electric demand related to the heating season of a multi-family house composed of three floors.

The heating purposes and domestic hot water production are satisfied by heating up the water contained within the tank. The MCHP system and natural gas-fired boiler co-operate in order to guarantee a given water temperature level (55 °C) within the hot water storage. The group of fan-coils is supplied by the combined tank. According to the European Standard EN12831:2003 [25], 20 °C was assumed as set-point indoor air temperature. Domestic hot water is produced by means of the internal heat exchanger IHE3 located in the tank; in the case of the temperature of the water

exiting IHE3 is lower than 45 °C, the required additional heat is provided by the auxiliary natural gas-fired boiler and transferred to the domestic hot water by means of the plate heat exchanger PHE.

The electricity generated by the cogeneration device is used directly into the building for the lighting systems, domestic appliances (such as vacuum cleaner, dishwasher, washing machine, PC, TVs, fridge), auxiliaries (pumps, fans, etc) or is exported to the electric grid; the electric grid is also used to cover peak demand.

3. Components and loads of the proposed system

Each component of the whole system was simulated by using the software TRNSYS [19], where each physical piece is modelled with a component (named “Type”) that is a FORTRAN source code model. In the following sections the main features of the Types used in this study for simulating each plant component are reported. Additional details can be found in Ref. [26].

3.1. Combined tank

The combined tank for both heating purposes and domestic hot water production was modelled in this study by means of the Type60f included in TRNSYS library. This model allows to calculate thermal stratification in the component: in this study ten temperature levels (nodes) were used in the tank; a uniform tank loss coefficient per unit area equal to 3.0 kJ/hm² K was assumed [27]. A vertical cylindrical hot water storage unit with one flow inlet (IF in Fig. 1) and one flow outlet (OF in Fig. 1) was considered: the cold water coming from the building enters the tank through the flow inlet IF, while hot water going towards the fan-coils installed within the building exits the tank through the flow outlet OF. The tank was equipped with three internal heat exchangers: the hot water coming from the MCHP unit flows through the internal heat exchanger located in lower part of the tank (IHE1 in Fig. 1); the hot water coming from the natural gas-fired boiler goes towards the internal heat exchanger located in upper part of the tank (IHE2 in Fig. 1); the third internal heat exchanger (IHE3 in Fig. 1) allows heat to be extracted for domestic hot water production. The main characteristics of the tank considered in this study are reported in Table 1 [28].

3.2. MCHP unit

A reciprocating internal combustion engine-based micro-cogeneration unit commercialized by AISIN SEIKI company [17] was

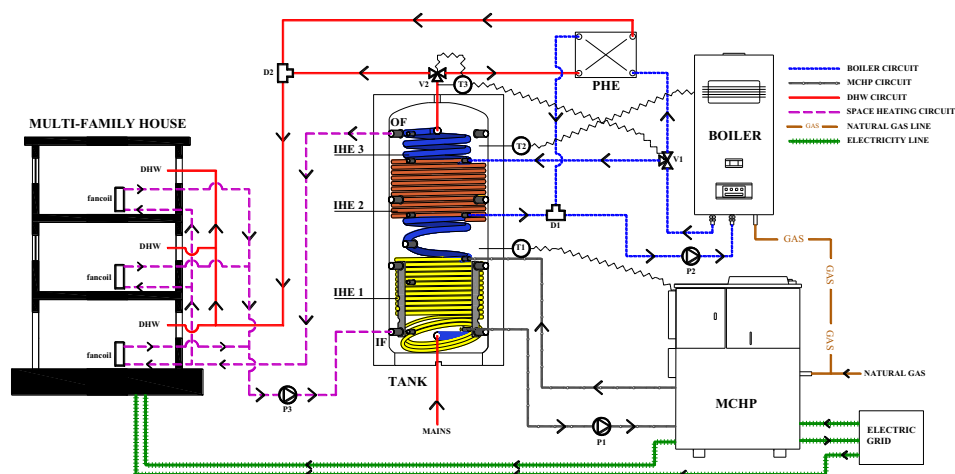


Fig. 1. Scheme of the system configuration analysed in this study.

Table 1
Main characteristics of the analysed hot water storage [28].

Tank volume (m ³)	0.855
Tank height (m)	2.040
Height of flow inlet (m)	0.125
Height of flow outlet (m)	1.691
Temperature levels used in the tank	10
Tank loss coefficient (kJ/hm ² K)	3.0
Destratification conductivity (kJ/hm K)	0
Number of internal heat exchangers	3
Height of thermostat controlling the MCHP (m)	0.816
Height of thermostat controlling the boiler (m)	1.836
The fraction of glycol contained in the IHE1 by volume (%)	0
IHE1 inside diameter (m)	0.027
IHE1 outside diameter (m)	0.029
IHE1 total surface area (m ²)	3.1
IHE1 length (m)	37.0
IHE1 wall conductivity (W/m K)	45
IHE1 material conductivity (W/m K)	45
Height of IHE1 inlet (m)	0.813
Height of IHE1 outlet (m)	0.144
The fraction of glycol contained in the IHE2 by volume (%)	0
IHE2 inside diameter (m)	0.026
IHE2 outside diameter (m)	0.028
IHE2 total surface area (m ²)	2.5
IHE2 length (m)	30.5
IHE2 wall conductivity (W/m K)	45
IHE2 material conductivity (W/m K)	45
Height of IHE2 inlet (m)	1.521
Height of IHE2 outlet (m)	1.048
The fraction of glycol contained in the IHE3 by volume (%)	0
IHE3 inside diameter (m)	0.023
IHE3 outside diameter (m)	0.025
IHE3 total surface area (m ²)	7.8
IHE3 length (m)	106.5
IHE3 wall conductivity (W/m K)	16
IHE3 material conductivity (W/m K)	16
Height of IHE3 inlet (m)	0.108
Height of IHE3 outlet (m)	1.703

investigated in this study. The main characteristics of this device are reported in Table 2.

Thermal power is recovered from the exhaust gases and the engine jacket of the micro-cogenerator by means of a water-glycol mixture and transferred to the water within the storage tank by using water as coolant. The MCHP device under investigation can operate under both electric and thermal load-following control strategies. Both operation logics were simulated in this study:

Table 2
Main characteristics of the MCHP unit [17].

AISIN SEIKI unit	
Model	GECC60A2
Engine type	Reciprocating internal combustion engine, water cooled, 4 strokes, 3 cylinders
Displacement (cm ³)	952
Speed revolution (rpm)	1600 ÷ 1800
Fuel	Natural gas, LPG
Generator type	Permanent – magnet type, synchronous generator 16 poles
Rated electric output (kW)	6
Rated thermal output (kW)	11.7
Operating sound at 1.0 m distance and 1.5 m height (dB)	54
Electric efficiency ^a at maximum load (%)	28.8
Thermal efficiency ^b at maximum load (%)	56.2

^a Ratio between electric output and primary power input.

^b Ratio between heat supplied to the end-user and primary power input.

- in the case of thermal load-following operation, the system operates according to the external temperature signal coming from the thermostat T1 (Fig. 1) placed on the tank near the entrance of the internal heat exchanger IHE1: when this temperature is lower than the set-point value (55 °C), the unit provides its maximum electric and thermal outputs; when the water temperature in the storage exceeds the set-point value, the unit is turned off. The electricity generation is a by-product and any unused excess of electricity is sent to the power line, that is also used to cover the peak load;
- in the case of electric load-following operation, the cogeneration system produces electricity by modulating the power supplied through the inverter on the basis of the electric demand. The MCHP system operates only in the case of the electric load is larger than 300 W: if the electric load is lower than 300 W the cogeneration unit does not start, while the MCHP system produces its maximum power in the case of the electric load is larger than its maximum electric output. Heat is also available during unit operation, even if its level depends on the system electric output.

The AISIN SEIKI unit has an internal control to keep the internal water-glycol temperature lower than a given value (about 70 °C), in order to prevent conditions endangering the engine block. This particular behaviour of the cogeneration device was taken into account in this study in the case of electric load-following operation: in the case of the temperature of the coolant coming out from the cogeneration device becomes higher than 70 °C, the recovered heat is dissipated into the external air through an air-to-water heat exchanger installed within the unit.

The Italian Law does not limit the daily operation time of cogeneration systems: as a consequence, in this study the MCHP unit was allowed to operate up to 24 h per day depending on electric/thermal requirements. The cogeneration unit was simulated by using the detailed dynamic model [21,22] developed within the Annex 42 of the International Energy Agency. This model was calibrated and validated for the AISIN SEIKI unit [17] on the basis of several laboratory tests performed by the authors [23,24] at the Built Environment Control Laboratory of the Second University of Naples. During the experiments the transient and steady-state operation of the cogeneration system was experimentally investigated upon varying the electric level, the coolant temperature, as well as the coolant flow rate. The experimental tests showed no significant variations of the electric efficiency of the micro-cogeneration device between transient and stationary regime; on the contrary, the values of thermal efficiency measured during transient operation were significantly lower than those measured during steady-state operation: this highlighted that neglecting the influence of thermal transition may imply a relevant overestimation of thermal energy supplied by the unit to the end-user, mainly during system operation at low electric levels. The analysis of the tests also indicated that both electrical and thermal efficiencies during steady-state operation are not significantly affected by both coolant temperature and coolant flow rate, while they are strongly dependent from the electric output of the unit: in particular, the experiments showed a thermal efficiency increasing when electric load reduces, and an electric efficiency increasing with the electrical power. The measurements were compared with the simulation data in order to empirically validate the calibrated Annex 42 model; the data measured during a 24 h dynamic test performed by applying a realistic daily load profile representing the Italian domestic non-HVAC demand profile for a multi-family house of five dwellings were used: the predicted fuel use, the electric output and heat recovery over the whole duration of the data set differed from measured values by –6.1%, –0.2% and –1.0%,

respectively. Taking into account the uncertainties associated to both measuring instruments and calibration procedure [23,24], it can be stated that the results of the performed validation activity demonstrated the suitability of the Annex 42 model in predicting the performance of the MCHP unit; in fact similar errors were detected in Refs. [29,30].

3.3. Boiler

A 20.0 kW_{th} natural gas-fired boiler [31] was considered in this study. The boiler was modelled in TRNSYS by using the Type6 included in TRNSYS library. The auxiliary heater is activated only in the case of (i) the water temperature within the tank (sensed by the thermostat T2 in Fig. 1) is lower than a given set-point value (55 °C), or when (ii) the domestic hot water temperature at the outlet of the internal heat exchanger IHE3 (sensed by the thermostat T3 in Fig. 1) is lower than 45 °C. In the case of temperature measured by thermostat T3 being lower than 45 °C, the full boiler output is utilized for hot water through the plate heat exchanger PHE.

According to the manufacturer data [31], 9.5 l/min as water flow rate was considered in this study.

The manufacturer [31] suggests 0.924 as boiler efficiency for a part load ratio equal to 30% and 0.927 as boiler efficiency in the case of operation at rated output. Therefore in this paper the boiler efficiency $\eta^{B,SP}$ was evaluated by considering a linear interpolation of the manufacturer data:

$$\eta^{B,SP} = 0.924 + 0.000214 \cdot (P_{th}^{B,SP} - 6.0) \quad (1)$$

Exhaust and combustion losses rates were not considered as negligible in this work: therefore the primary power consumption of the boiler was evaluated as follows:

$$P_p^{B,SP} = P_{th}^{B,SP} / \eta^{B,SP} \quad (2)$$

According to the Italian Law [32], Italy is divided in 6 different climatic zones (named A, B, C, D, E, F) based on the Heating Degree Days (HDD) index [33]. A maximum daily operation time for the heating system depending on the climatic zone is specified in Ref. [32]; as a consequence, the boiler was allowed to operate only during the time intervals specified in Table 3 as a function of both the city and day (week day and weekend day are distinguished). Out of these periods the boiler was turned off for heating purposes; the boiler is allowed to operate up to 24 h per day if thermal energy is required for producing domestic hot water at 45 °C.

3.4. Building characteristics and loads

The geometrical layout of the building investigated in this report is basically a multiplication of a single family house type building geometry. The main geometrical characteristics of each floor and the building orientation are shown in Fig. 2. All three floors have the same useable floor area (96.0 m²), while the net height of each single floor is 3.0 m. Five windows were considered for each single floor.

Starting from 1st January 2010, the Italian Law [18] specifies the threshold values of transmittance for both walls and windows of renovated buildings depending on (i) the climatic zone where the building is located, and (ii) the wall type (external wall, ground and roof). These threshold values of transmittance U_{lim} for property renovations located in Palermo, Napoli, Roma e Milano are specified for walls and windows, respectively, in Tables 4 and 5.

In Table 4 the characteristics of building walls considered in this study are also specified: in particular, the internal (h_i) and external (h_e) convective and radiative heat transfer coefficients of walls, wall transmittance (U_{wall}), layers material, thickness (s), density (ρ), specific heat (c) and thermal conductivity (λ) are reported for each wall type as well as for each city. As it can be derived from Table 4, each wall is compliant to the requirements of Italian Law [18], with transmittance values equated to the given threshold values: this result was obtained by adjusting the building insulation upon varying the climatic zone. The values of h_i and h_e were derived by the European Standard EN ISO 6946 [34], while the values of ρ , c and λ were defined based on Italian Standard UNI 10351:1994/EC [35].

The main characteristics of windows are reported in Table 5: in particular, the internal (h_i) and external (h_e) convective and radiative heat transfer coefficients of windows, frame transmittance U_{frame} , glazing transmittance $U_{glazing}$, window type, glazing width, spacing width, spacing gas, ratio between frame area A_{frame} and window (glazing + frame) area A_{window} are specified for each city. As it can be derived from Table 5, windows transmittance values are compliant to the requirements of Italian Law [18] with transmittance values equated to the given threshold values; values of U_{frame} and U_{window} were calculated based on the European Standard EN ISO 10077-1 [36]; all windows are provided with shadings, whose zone and wall reflection coefficients were considered equal to 0.5. According to the Italian Law [37], the area of each window was defined as the 12.5% of the ground area of the room where the window is located.

The Italian Law [18] specifies the duration of the heating season depending on the Italian region where the plant is located: according to the limits specified in Ref. [18], in this study the following periods of simulations were considered:

- ✓ Palermo: from December 1st to March 31st;
- ✓ Napoli: from November 15th to March 31st;
- ✓ Roma: from November 1st to April 15th;
- ✓ Milano: from October 15th to April 15th.

A maximum daily operation time for the heating system depending on the climatic zone is specified in Ref. [18]. As a consequence, the indoor air temperature was controlled only during the time intervals specified in Table 3: out of these time intervals the indoor air temperature was not controlled.

Heat coming from occupants, personal computers and lighting systems was assumed to contribute to the internal gains of the building. Fig. 3 shows the number of occupants of each single floor and the occupants-related sensible heat gain of each single floor as

Table 3
Time intervals during which the boiler can operate for heating purposes.

Week day				Weekend day			
Palermo (climatic zone B, HDD = 751)	Napoli (climatic zone C, HDD = 1034)	Roma (climatic zone D, HDD = 1415)	Milano (climatic zone E, HDD = 2404)	Palermo (climatic zone B, HDD = 751)	Napoli (climatic zone C, HDD = 1034)	Roma (climatic zone D, HDD = 1415)	Milano (climatic zone E, HDD = 2404)
7:30–10:00	7:30–11:00	6:30–11:00	6:30–12:00	8:30–10:00	8:30–11:00	8:30–12:00	8:30–13:30
16:00–21:30	15:00–21:30	15:00–22:30	14:30–23:00	16:00–22:30	15:00–22:30	14:00–22:30	14:30–23:30

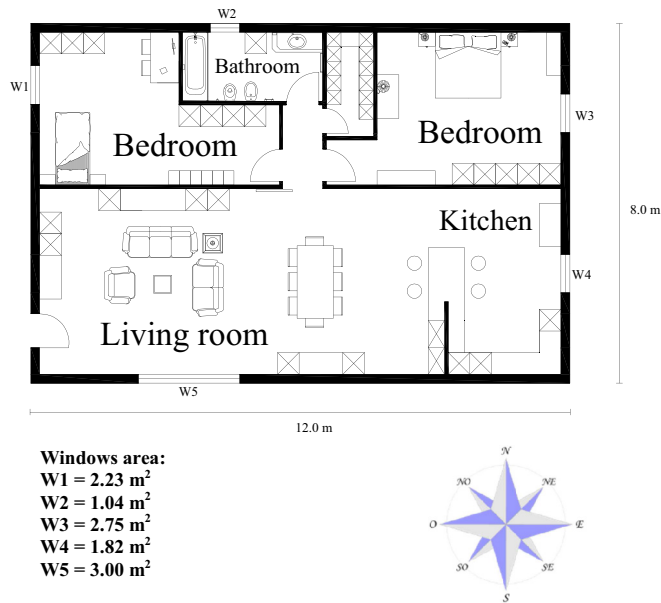


Fig. 2. Main geometrical characteristics of a single flat of the whole multi-family house.

a function of the time during a week day (Fig. 3a) and a weekend day (Fig. 3b). Sensible heat coming from each occupant was assumed equal to 75.0 W: this value is suggested by the Standard ISO 7730 [38] in the case of light work/typing as degree of activity.

Fig. 4 shows the sensible heat flux related to the lighting appliances installed within the rooms of each single flat. Light sources with an installed total electric capacity of 294.0 W were considered; thermal power coming from each lighting system was assumed equal to the 75% of its nominal electric capacity. Sensible

heat produced by lighting systems was considered as transferred to the indoor air by both radiation (70%) and convection (30%) [39].

Concerning the infiltration, the European Standard EN12831:2003 [25] was used to calculate the air exchange rate, i.e. the number of interior volume air changes that occur per hour, induced by wind and stack effect on the building envelope: based on this European Standard, the air exchange rate was assumed equal to 0.28 h⁻¹.

The internal gains coming from occupants, personal computers and lighting appliances for the entire building were generated through the superposition of three of the single flat profiles. No difference among the four cities was considered in terms of internal gains.

A group of fan-coils, supplied by the hot water storage, was installed into the building in order to balance the space heating sensible load. A temperature difference of 5 °C was assumed for the hot water crossing the fan-coils, with a variable-flow pump controlling the fan-coils outlet temperature.

The Type56a (included in TRNSYS library) was used for modeling the building envelope, indoor air set-point temperature, infiltration and internal gains. Type15-6 (included in TRNSYS library) was used for reading the external EnergyPlus weather data files [40] of each city. A specific EnergyPlus weather data file was considered for each city.

Fig. 5 reports the whole building thermal load-duration diagram with the heat-demand values sorted in descending order for each city under consideration. As it can be derived from Fig. 5, space heating demand has a quite different duration depending on the city under investigation: it is equal to about 940 h for Palermo, 1370 h for Napoli, 1860 h for Roma, and 2550 h for Milano. In addition it can be noticed that the building sensible thermal load is lower than the nominal thermal output of the MCHP unit (11.7 kW) for the most part of the system operation time whatever the city under consideration is. The maximum thermal load is always 31.7 kW: this value was set in TRNSYS simulations as the sum of the

Table 4
Characteristics of building walls.

Wall type	U_{lim} (W/m ² K)	h_i (W/m ² K)	h_e (W/m ² K)	U_{wall} (W/m ² K)	Layer materials	s (m)	ρ (kg/m ³)	c (kJ/Kg k)	λ (W/m K)	
External wall	Palermo = 0.48	7.7	25.0	Palermo = 0.48	Gypsum plaster	0.02	900	1.00	0.250	
	Napoli = 0.40			Bricks	0.33	1800	0.84	0.720		
	Roma = 0.36			Expanded Polyester	Palermo = 0.053	20	1.20	0.041		
	Milano = 0.34				Napoli = 0.070					
Roof		10.0	25.0							
	Palermo = 0.38									
	Napoli = 0.38			Gypsum plaster	0.02	900	1.00	0.250		
	Roma = 0.32			Gypsum plaster	0.015	1800	1.00	0.700		
	Milano = 0.30			Cement and bricks	0.300	1000	0.84	0.300		
				Concrete	0.084	1900	0.84	1.060		
				Bitumen	0.010	1200	1.00	0.170		
				Expanded polyester	Palermo = 0.052	20	1.20	0.041		
					Napoli = 0.052					
					Roma = 0.072					
					Milano = 0.080					
	Ground				5.9	25.0				
Palermo = 0.49										
Napoli = 0.42		Sand	0.050	1700			0.84	1.400		
Roma = 0.36		Lime and cement adhesive	0.010	1500			1.00	0.720		
Milano = 0.33		Tiles	0.010	2300			0.84	0.720		
		Tiles	0.010	2300			0.84	0.720		
		Lime and cement adhesive	0.010	1500			1.00	0.720		
		Sand	0.050	1700			0.84	1.400		
		Expanded polyester	Palermo = 0.026	20			1.20	0.041		
			Napoli = 0.040							
			Roma = 0.057							
			Milano = 0.067							

Table 5
Characteristics of windows.

	U_{lim} (W/m ² K)	h_i (W/m ² K)	h_e (W/m ² K)	U_{frame} (W/m ² K)	U_{glazing} (W/m ² K)	Window type	Glazing width (mm)	Spacing width (mm)	Spacing gas	$A_{\text{frame}}/A_{\text{window}}$ (%)
Palermo	3.0	7.7	25.0	3.96	2.83	Double glazing	4	16	Argon	15
Napoli	2.6			2.94	2.54		6			
Roma	2.4			7.90	1.43		4	15		
Milano	2.2			6.56	1.53					

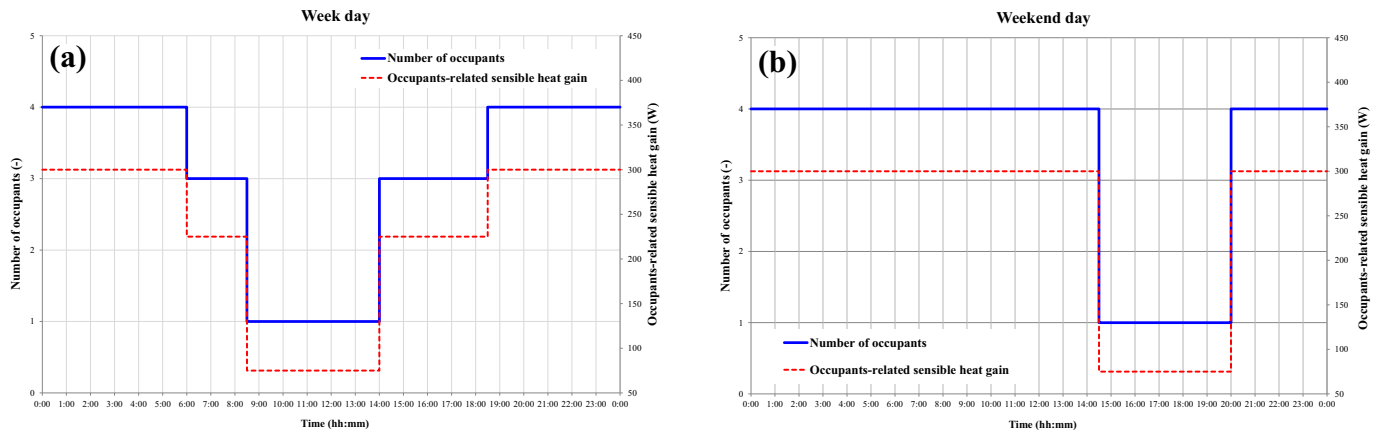


Fig. 3. Occupants-related sensible heat gains for a single flat during week day (a) and weekend day (b) whatever the city is.

thermal output of the boiler of the proposed system (20.0 kW) and the maximum thermal output of the MCHP unit (11.7 kW).

Fig. 6 shows the values of thermal energy required for heating purposes of the whole building per unit area as a function of both the city and the simulation period. According to this figure, it is worth noting that, whatever the period under investigation is, the maximum and the minimum amounts of thermal energy are required in the case of the building located in Milano and Palermo, respectively; the thermal energy required by the building located in Napoli is always larger than that one used by the building located in Roma.

In this study the domestic hot water demand profile with an average basic load of 200 l/day in the time scale of 1 min specified

within IEA-SHC Task 26 [41,42] was used for estimating the domestic hot water demand of each single flat. Fig. 7a shows the daily domestic hot water demand of each single flat for three typical days (December 31st, January 31st and March 15th), while Fig. 7b reports the hot water demand-duration diagram of each single flat as a function of the city, with the domestic hot water flow rate values sorted in descending order. In this paper the domestic hot water demand profile of the entire building was generated through the superposition of three of the single flat profiles. The temperature of cold water coming from the mains was derived by considering the distribution profile defined by the Type15-6 (included in TRNSYS library).

Fig. 8a highlights the daily electric demand profile resulting from the operation of both lighting systems and other domestic

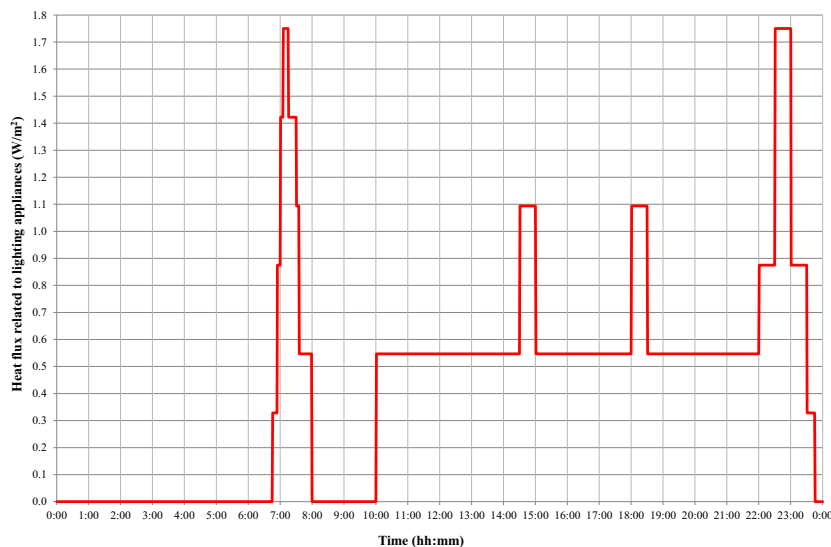


Fig. 4. Daily heat flux profile associated to the lighting appliances of a single floor whatever the city is.

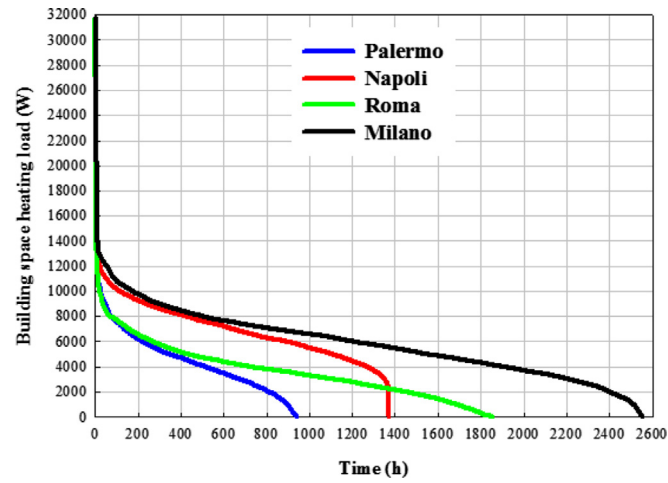


Fig. 5. Thermal load-duration diagram with the heat-demand values sorted in descending order for each city under consideration.

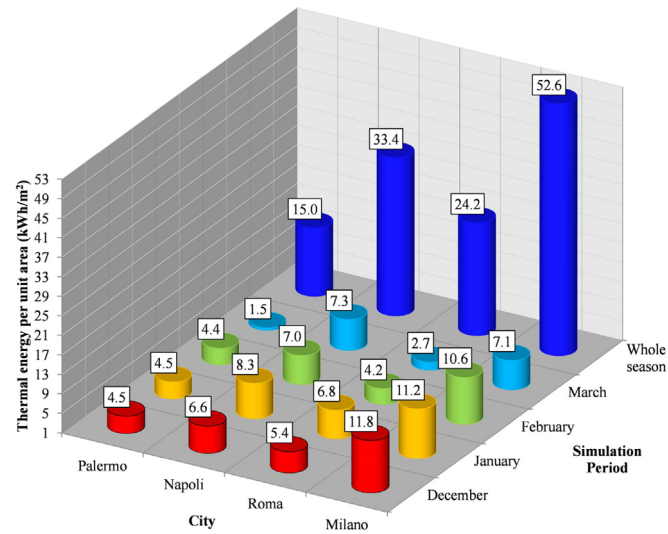


Fig. 6. Thermal energy required for building heating purposes per unit area as a function of the city and the simulation period.

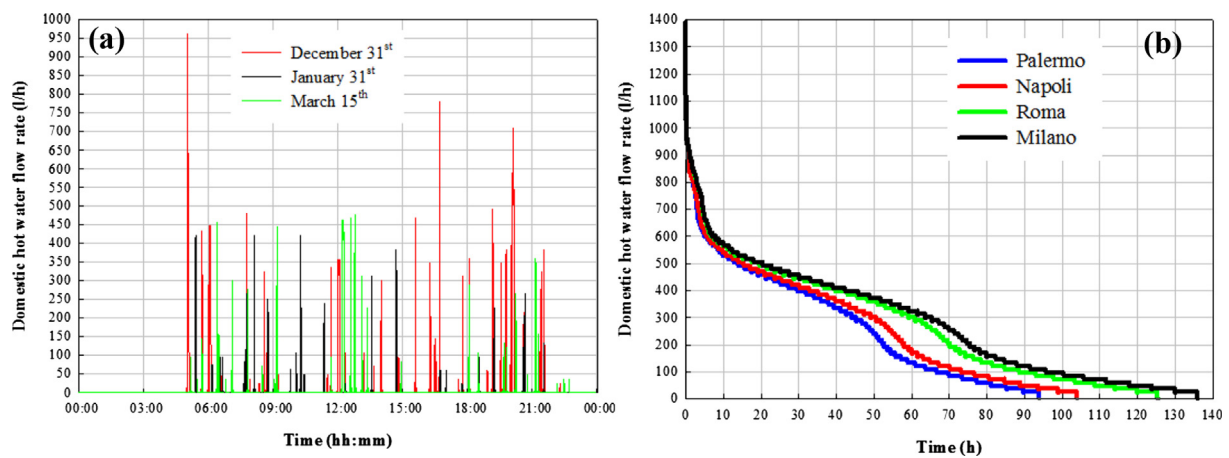


Fig. 7. Single flat daily domestic hot water demand profile during 3 typical days (a) and single flat domestic hot water duration curve (b).

appliances (such as vacuum cleaner, dishwasher, washing machine, PC, TVs, fridge) assumed in this study for each single flat. The electric consumptions of each appliance were derived from Ref. [43]. The daily electric demand profile of the whole building was defined through the superposition of three of the single flat profiles reported in Fig. 8a. The electric demand profile considered in this study corresponds to an electric consumption for the whole building equal to about 109.7 Wh/m² per day. Fig. 8b shows the electric load-duration diagram (with the electric-demand values sorted in descending order) for each city under consideration. This figure shows that the building requires an electric power larger than the nominal electric output of the micro-cogeneration unit (6.0 kW) for a time interval ranging from 52 h (Palermo) and 79 h (Milano).

The electric consumption of the pumps and the fan of heat dissipator were also taken into account during the simulations.

4. Description of the reference system

The main focus of this study is comparing the environmental performance of the proposed plant (SP) based on a micro-cogeneration device with those of a conventional system (CS) based on separate energy production. In the following a conventional system composed of a natural gas-fired boiler (for thermal energy production) and a power plant mix connected to the electric grid (for electricity production) is considered. The comparison was performed by assuming for the reference system the same electric and thermal energy output of the proposed system.

A 32.0 kW_{th} natural gas-fired boiler [31] was selected for the thermal energy production within the reference system. The boiler manufacturer [31] suggests a value of 0.911 as boiler efficiency for a part load ratio equal to 30% and a value of 0.937 as boiler efficiency in the case of operation at rated output; in this study the boiler efficiency of the conventional system $\eta^{B,CS}$ was evaluated by considering a linear interpolation of the manufacturer data:

$$\eta^{B,CS} = 0.911 + 0.001067 \cdot (P_{th}^{B,CS} - 10.44) \quad (3)$$

The exhaust and combustion losses rates were not considered as negligible in this study. Therefore the primary power consumption of the boiler considered for the conventional system was evaluated as follows:

$$P_p^{B,CS} = P_{th}^{B,CS} / \eta^{B,CS} \quad (4)$$

Concerning the efficiency of the power plant mix connected to the national electric grid η_{pp} , a figure of 0.461 was assumed: this value represents the power plant average efficiency in Italy, including transmission losses [44].

5. Methodology, results and discussion

In this section NO_x and CO emissions of the proposed system were evaluated and compared with those associated to the conventional system assumed as reference.

Regardless of the excess air, any combustion process is characterized by a certain amount of by-products such as, in particular, CO not oxidized into CO₂. In general, the emissions of this pollutant are not easy to calculate, since they depend on several specific combustion kinetic characteristics, such as temperature, oxygen excess, mixing aspects, and so forth. In addition, the emission levels are commonly kept at a minimum at the design stage, and their increase during operation is an indicator of lower combustion efficiency (for instance, due to bad fuel-air mixing or bad maintenance) [11,13,45]. The NO_x formation mainly depends on temperature in the combustion chamber, retention time in the primary combustion zone, as well as the relative air-to-fuel ratio (i.e. the ratio of the actual air to fuel ratio to the stoichiometric one) that affects not only the NO_x production, but also the CO emissions [11]. NO_x and CO emissions of the micro-cogeneration system [18] under investigation in this paper were not measured by the authors, but they were derived from the experimental data measured at both the Advanced Engine Technology Ltd. and the Canadian Centre for Housing Technology twin research homes [20]. The measurement results were obtained by using a Horiba PG250 portable gas analyzer [46]; this analyzer was connected to the MCHP unit by means of a sampling probe inserted approximately 50 cm into the flue outlet. Emissions of NO_x and CO were tested by operating the cogeneration device under electric load-following control strategy, with the electric load varied in stepwise manner from about 2.5 kW to about 6 kW; levels of NO_x and CO emissions were recorded at a frequency of 1 s⁻¹. Testing was performed in two phases: in the first phase cold start testing was performed, while the second phase was carried out for considering the case of warm-start. The cold weather tests began with a cold start, where the

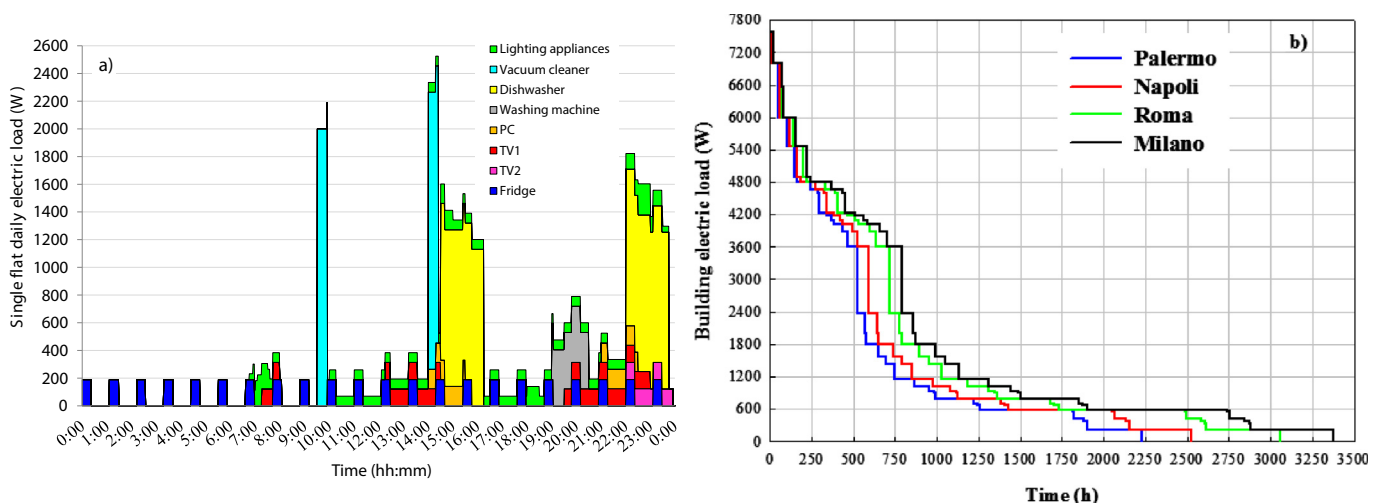


Fig. 8. Daily electric demand profile for each single flat (a) and building electric load-duration diagrams (b).

engine had been kept outside for 2.5 h in -17°C ambient air prior to start-up; cold start testing was done with the unit installed in an environmental chamber for soaking in temperatures down to -40°C . The warm weather testing phase was conducted with the cogeneration unit installed outdoors. In this paper only the values measured during the second phase were considered. In addition it must be highlighted that the unit experimentally investigated in Ref. [20] was the model commercialized by the AISIN SEIKI company [17] within the non-European Union market: this model is not equipped with the catalytic converter for abating the CO emissions; the model commercialized by the AISIN SEIKI company [17] for the European Union market is equipped with the catalytic converter, and therefore it is characterized by lower emissions of CO.

Fig. 9 shows the emissions of both NO_x and CO as a function of the electric output of the MCHP system measured during steady-state operation in warm weather conditions as reported in Ref. [20]. As it can be derived from this figure, steady-state NO_x levels were about 60 ppm at 6 kW and 18 ppm at 2.5 kW; CO emissions of about 560 ppm at full power and 800 ppm at 2.5 kW were observed. The NO_x and CO emissions were strongly correlated with electric load within the range examined. Emissions were measured by Lombardi et al. [20] also during start-up, shutdown and load transients; the highest CO emissions were observed during start-up, where levels of 1400 ppm were obtained briefly approximately 5 min after engine firing; the NO_x levels did not noticeably spike during start-up. In the following only the emissions measured during steady-state operation (reported in Fig. 9) were taken into account.

In this study the emissions of both NO_x and CO due to the MCHP operation were evaluated by using the following formulae:

$$e_{\text{NO}_x}^{\text{MCHP}} = 0.5346 \cdot (p_{\text{el}}^{\text{MCHP}})^3 - 2.8313 \cdot (p_{\text{el}}^{\text{MCHP}})^2 + 5.5675 \cdot p_{\text{el}}^{\text{MCHP}} + 13.707 \quad (5)$$

$$e_{\text{CO}}^{\text{MCHP}} = -4.779 \cdot (p_{\text{el}}^{\text{MCHP}})^3 + 66.843 \cdot (p_{\text{el}}^{\text{MCHP}})^2 - 361.02 \cdot p_{\text{el}}^{\text{MCHP}} + 1362.5 \quad (6)$$

where $p_{\text{el}}^{\text{MCHP}}$ is the electric output of the cogeneration device. The values provided by Eqs. (5) and (6) are expressed in parts per million. Both Eqs. (5) and (6) were defined by correlating the experimental data reported in Fig. 9 with a third order polynomial function; a coefficient of determination equal to one was obtained in both cases within the range of electric power experimentally

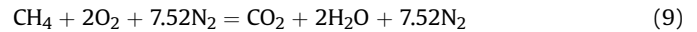
investigated in Ref. [20]. Trend lines expressed by Eqs. (5) and (6) are also reported in Fig. 9.

The emissions of both NO_x and CO due to the MCHP operation expressed in kilograms were obtained starting from Eqs. (5) and (6) by means of the following formulae:

$$m_{\text{NO}_x}^{\text{MCHP}} = e_{\text{NO}_x}^{\text{MCHP}} / 10^6 \cdot M_{\text{NO}_x} / M_{\text{exh}} \cdot \dot{m}_{\text{fuel}} \cdot (1 + \alpha) \cdot \text{STS} \quad (7)$$

$$m_{\text{CO}}^{\text{MCHP}} = e_{\text{CO}}^{\text{MCHP}} / 10^6 \cdot M_{\text{CO}} / M_{\text{exh}} \cdot \dot{m}_{\text{fuel}} \cdot (1 + \alpha) \cdot \text{STS} \quad (8)$$

where M is the molar mass of the chemical compound ($M_{\text{NO}_x} = 44 \text{ kg/kmol}$, $M_{\text{CO}} = 28 \text{ kg/kmol}$), M_{exh} is the average molar mass of exhaust gases (assumed equal to 29 kg/kmol), $\dot{m}_{\text{fuel}}$ is the fuel mass flow rate consumed by the MCHP unit (calculated by assuming the lower heating value of natural gas equal to $49,599 \text{ kJ/kg}$ [47]), STS is the Simulation Time Step used in this study (equal to 1 min). The parameter α represents the air to fuel ratio; its assumed value ($17.12 \text{ kg}_{\text{air}}/\text{kg}_{\text{fuel}}$) was obtained by considering the following complete stoichiometric methane combustion:



The emissions of NO_x and CO due to both the operation of the natural gas-fired boiler of the proposed system and the production of electricity purchased from the central electric grid were calculated by using the standard emission factors approach suggested in Ref. [12]. According to this approach, the mass of a given pollutant x emitted while producing the energy output E can be worked out as:

$$m_x = u_x^E \cdot E \quad (10)$$

where u_x^E is the energy output-based emission factor that is the specific emissions of x per unit of E . As a consequence, the mass of both NO_x and CO emitted by the natural gas-fired boiler of the proposed system were calculated as follows:

$$m_{\text{NO}_x}^{\text{B,SP}} = u_{\text{NO}_x}^{E_p} \cdot E_{\text{th}}^{\text{B,SP}} / \eta^{\text{B,SP}} \quad (11)$$

$$m_{\text{CO}}^{\text{B,SP}} = u_{\text{CO}}^{E_p} \cdot E_{\text{th}}^{\text{B,SP}} / \eta^{\text{B,SP}} \quad (12)$$

where $u_{\text{NO}_x}^{E_p}$ and $u_{\text{CO}}^{E_p}$ are, respectively, the NO_x and CO emission factors associated to the natural gas consumption, $E_{\text{th}}^{\text{B,SP}}$ is the thermal energy produced by the boiler of the proposed system, and $\eta^{\text{B,SP}}$ is the efficiency of the boiler of the proposed system. The values of $\eta^{\text{B,SP}}$ were calculated by means of Eq. (1).

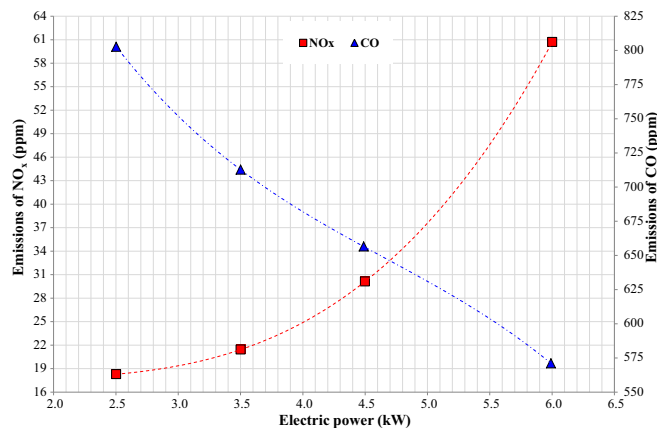


Fig. 9. Steady-state emissions during warm weather testing [20].

In this study the NO_x and CO emission factors associated to the natural gas consumption were assumed equal to $0.2 \text{ gNO}_x/\text{kWh}_p$ and $0.04 \text{ gCO}/\text{kWh}_p$, respectively, according to the values suggested in Ref. [12]: these values represent the equivalent NO_x and CO emissions for a primary energy unit consumed by burning out natural gas.

The mass of both NO_x and CO emitted for producing the electricity purchased from the central electric grid were obtained by using the following formulae:

$$m_{\text{NO}_x}^{\text{grid}} = u_{\text{NO}_x}^{E_{\text{el}}} \cdot E_{\text{el}}^{\text{grid}} \quad (13)$$

$$m_{\text{CO}}^{\text{grid}} = u_{\text{CO}}^{E_{\text{el}}} \cdot E_{\text{el}}^{\text{grid}} \quad (14)$$

The average NO_x and CO emissions for producing electricity depend upon the technology mix adopted. Thus, the emissions are significantly lower where the generation system is based upon renewable sources such as hydroelectric power. Italy has a power generation system with no nuclear power and with about 20% of hydro-electricity; the main part is thermal-based, with a mix of fuels including coal, oil and natural gas. According to the values suggested in Ref. [12], in this paper the NO_x and CO emission factors for electricity production were assumed equal to $0.5 \text{ gNO}_x/\text{kWh}_{\text{el}}$ and $0.3 \text{ gCO}/\text{kWh}_{\text{el}}$, respectively: these value represents the equivalent NO_x and CO emissions for an electric energy unit consumed according to the Italian scenario.

Table 6 highlights the MCHP operation time, the electric energy $E_{\text{el}}^{\text{MCHP}}$ produced by the cogeneration device, the thermal energy $E_{\text{th}}^{\text{MCHP}}$ supplied to the water within the tank by the MCHP unit, the thermal energy $E_{\text{th}}^{\text{B,SP}}$ produced by the boiler of the proposed system, and the electric energy $E_{\text{el}}^{\text{grid}}$ purchased from the central grid. These parameters are reported as a function of both the city under consideration and the MCHP unit control logic. This table shows that, in the case of thermal load-following logic, the thermal energy supplied by the MCHP system to the tank is $4.7 \div 7.7$ times larger than those produced by the boiler, while the electric output of the AISIN SEIKI unit is $1.0 \div 2.9$ times greater than the electric energy purchased from the central national grid; in the case of electric load-control strategy, the values of $E_{\text{th}}^{\text{MCHP}}$ are $0.4 \div 2.6$ times the values of $E_{\text{th}}^{\text{B,SP}}$, while $E_{\text{el}}^{\text{MCHP}}$ is $11.7 \div 13.1$ times greater than $E_{\text{el}}^{\text{grid}}$.

Table 7 shows the mass of both NO_x and CO emitted by each single components of the proposed system (the MCHP device, the natural gas-fired boiler as well as the electric grid) during the whole heating season as a function of both the city under consideration and the MCHP unit control logic. This table highlights that:

- under electric load following logic, the emissions of NO_x associated to the MCHP unit are about $1.1 \div 2.1$ times larger than those associated to the boiler, and about $6.6 \div 7.3$ times greater than those related to the electric grid;
- under electric load following logic, the emissions of CO associated to the MCHP unit are about $107.9 \div 197.9$ times larger than those associated to the boiler and about $326.5 \div 356.1$ times greater than those related to the electric grid;
- under thermal load following logic, the emissions of NO_x associated to the MCHP unit are about $3.9 \div 5.6$ times larger than those associated to the boiler, and about $0.8 \div 2.2$ times the values related to the electric grid;
- under thermal load following logic, the emissions of CO associated to the MCHP unit are about $168.9 \div 261.0$ times larger than those associated to the boiler and about $19.1 \div 44.6$ times greater than those related to the electric grid;

Table 6

Energy flows entering and exiting the proposed system during the whole heating season.

		Electric load-following operation	Thermal load-following operation
Palermo	MCHP operation time (h)	2136	1180
	$E_{\text{el}}^{\text{MCHP}}$ (kJ)	$2.02\text{E} + 07$	$1.38\text{E} + 07$
	$E_{\text{th}}^{\text{MCHP}}$ (kJ)	$3.75\text{E} + 07$	$3.79\text{E} + 07$
	$E_{\text{th}}^{\text{B,SP}}$ (kJ)	$1.51\text{E} + 07$	$4.90\text{E} + 06$
	$E_{\text{el}}^{\text{grid}}$ (kJ)	$1.72\text{E} + 06$	$1.34\text{E} + 07$
	MCHP operation time (h)	2541	1639
Napoli	$E_{\text{el}}^{\text{MCHP}}$ (kJ)	$2.47\text{E} + 07$	$2.44\text{E} + 07$
	$E_{\text{th}}^{\text{MCHP}}$ (kJ)	$4.33\text{E} + 07$	$5.68\text{E} + 07$
	$E_{\text{th}}^{\text{B,SP}}$ (kJ)	$3.09\text{E} + 07$	$1.20\text{E} + 07$
	$E_{\text{el}}^{\text{grid}}$ (kJ)	$1.88\text{E} + 06$	$1.25\text{E} + 07$
	MCHP operation time (h)	3132	1932
	$E_{\text{el}}^{\text{MCHP}}$ (kJ)	$3.02\text{E} + 07$	$2.21\text{E} + 07$
Roma	$E_{\text{th}}^{\text{MCHP}}$ (kJ)	$5.38\text{E} + 07$	$6.01\text{E} + 07$
	$E_{\text{th}}^{\text{B,SP}}$ (kJ)	$2.08\text{E} + 07$	$8.11\text{E} + 06$
	$E_{\text{el}}^{\text{grid}}$ (kJ)	$2.37\text{E} + 06$	$1.93\text{E} + 07$
	MCHP operation time (h)	3563	2822
	$E_{\text{el}}^{\text{MCHP}}$ (kJ)	$3.57\text{E} + 07$	$4.28\text{E} + 07$
	$E_{\text{th}}^{\text{MCHP}}$ (kJ)	$1.66\text{E} + 07$	$9.55\text{E} + 07$
Milano	$E_{\text{th}}^{\text{B,SP}}$ (kJ)	$4.35\text{E} + 07$	$1.76\text{E} + 07$
	$E_{\text{el}}^{\text{grid}}$ (kJ)	$2.86\text{E} + 06$	$1.49\text{E} + 07$

- in comparison to the electric load-control strategy, the thermal load-following operation is characterized by $1.3 \div 1.4$ times larger total NO_x emissions and $0.5 \div 0.7$ times lower total CO levels.

As above-mentioned, the emissions of NO_x and CO associated to the proposed system (SP) were compared with those of the conventional system (CS) described in the Section 4. The comparison was performed by means of the following indicators:

$$R_{\text{NO}_x} = m_{\text{NO}_x}^{\text{SP}} / m_{\text{NO}_x}^{\text{CS}} \quad (15)$$

Table 7

Mass of both NO_x and CO emitted by each single components of the proposed system during the whole heating season.

		Electric load-following operation	Thermal load-following operation
Palermo	$m_{\text{NO}_x}^{\text{MCHP}}$ (kg)	$1.58\text{E} + 00$	$1.52\text{E} + 00$
	$m_{\text{NO}_x}^{\text{B,SP}}$ (kg)	$8.36\text{E} - 01$	$2.72\text{E} - 01$
	$m_{\text{NO}_x}^{\text{grid}}$ (kg)	$2.39\text{E} - 01$	$1.86\text{E} + 00$
	$m_{\text{CO}}^{\text{MCHP}}$ (kg)	$3.12\text{E} + 01$	$1.42\text{E} + 01$
	$m_{\text{CO}}^{\text{B,SP}}$ (kg)	$1.67\text{E} - 01$	$5.45\text{E} - 02$
	$m_{\text{CO}}^{\text{grid}}$ (kg)	$9.54\text{E} - 02$	$7.46\text{E} - 01$
Napoli	$m_{\text{NO}_x}^{\text{MCHP}}$ (kg)	$1.91\text{E} + 00$	$2.59\text{E} + 00$
	$m_{\text{NO}_x}^{\text{B,SP}}$ (kg)	$1.72\text{E} + 00$	$6.64\text{E} - 01$
	$m_{\text{NO}_x}^{\text{grid}}$ (kg)	$2.61\text{E} - 01$	$1.73\text{E} + 00$
	$m_{\text{CO}}^{\text{MCHP}}$ (kg)	$3.71\text{E} + 01$	$2.24\text{E} + 01$
	$m_{\text{CO}}^{\text{B,SP}}$ (kg)	$3.44\text{E} - 01$	$1.33\text{E} - 01$
	$m_{\text{CO}}^{\text{grid}}$ (kg)	$1.04\text{E} - 01$	$6.92\text{E} - 01$
Roma	$m_{\text{NO}_x}^{\text{MCHP}}$ (kg)	$2.37\text{E} + 00$	$2.39\text{E} + 00$
	$m_{\text{NO}_x}^{\text{B,SP}}$ (kg)	$1.16\text{E} + 00$	$4.51\text{E} - 01$
	$m_{\text{NO}_x}^{\text{grid}}$ (kg)	$3.30\text{E} - 01$	$2.68\text{E} + 00$
	$m_{\text{CO}}^{\text{MCHP}}$ (kg)	$4.57\text{E} + 01$	$2.14\text{E} + 01$
	$m_{\text{CO}}^{\text{B,SP}}$ (kg)	$2.31\text{E} - 01$	$9.02\text{E} - 02$
	$m_{\text{CO}}^{\text{grid}}$ (kg)	$1.32\text{E} - 01$	$1.07\text{E} + 00$
Milano	$m_{\text{NO}_x}^{\text{MCHP}}$ (kg)	$2.77\text{E} + 00$	$4.46\text{E} + 00$
	$m_{\text{NO}_x}^{\text{B,SP}}$ (kg)	$2.42\text{E} + 00$	$9.80\text{E} - 01$
	$m_{\text{NO}_x}^{\text{grid}}$ (kg)	$3.98\text{E} - 01$	$2.07\text{E} + 00$
	$m_{\text{CO}}^{\text{MCHP}}$ (kg)	$5.22\text{E} + 01$	$3.69\text{E} + 01$
	$m_{\text{CO}}^{\text{B,SP}}$ (kg)	$4.83\text{E} - 01$	$1.96\text{E} - 01$
	$m_{\text{CO}}^{\text{grid}}$ (kg)	$1.59\text{E} - 01$	$8.28\text{E} - 01$

$$R_{CO} = m_{CO}^{SP} / m_{CO}^{CS} \quad (16)$$

where the NO_x and CO emissions of both the proposed system and the conventional system are calculated as follows:

$$m_{NO_x}^{SP} = m_{NO_x}^{MCHP} + m_{NO_x}^{B,SP} + m_{NO_x}^{grid} \quad (17)$$

$$m_{CO}^{SP} = m_{CO}^{MCHP} + m_{CO}^{B,SP} + m_{CO}^{grid} \quad (18)$$

$$m_{NO_x}^{CS} = u_{NO_x}^{Ep} \cdot (E_{th}^{MCHP} + E_{th}^{B,SP}) / \eta^{B,CS} + u_{NO_x}^{E_{el}} \cdot (E_{el}^{MCHP} + E_{el}^{grid}) \quad (19)$$

$$m_{CO}^{CS} = u_{CO}^{Ep} \cdot (E_{th}^{MCHP} + E_{th}^{B,SP}) / \eta^{B,CS} + u_{CO}^{E_{el}} \cdot (E_{el}^{MCHP} + E_{el}^{grid}) \quad (20)$$

A value of R_{NO_x} and R_{CO} lower than one means that the proposed system allows to reduce the emissions of NO_x and CO, respectively, with respect to the system based on separate energy production.

Figs. 10 and 11 report the values of R_{NO_x} and R_{CO} as a function of both the city under consideration and the MCHP unit control logic under thermal and electric load-control strategy, respectively. These figures highlight that:

- ✓ whatever the city and MCHP control logic are, the proposed system allows for reducing the NO_x emissions in comparison to the conventional system: the NO_x levels associated to the proposed system are $0.44 \div 0.59$ times lower than those related to the reference system;
- ✓ whatever the city and MCHP control logic are, the CO emissions associated to the conventional system are substantially negligible with respect to those of the proposed system: the CO levels associated to the proposed system are $7.37 \div 17.47$ times larger than those related to the reference system. About this point, it should be highlighted that this result is mainly due to the fact that in this study the MCHP unit commercialized by the AISIN SEIKI company [17] without the catalytic converter was considered;
- ✓ whatever the city, the reduction of the NO_x emissions is more pronounced in the case of electric load-following logic in comparison to the thermal load-control strategy;

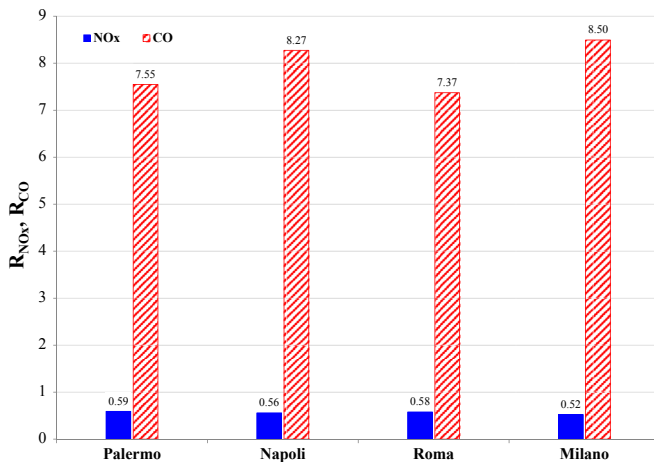


Fig. 10. R_{NO_x} and R_{CO} under thermal load-following operation as a function of the city.

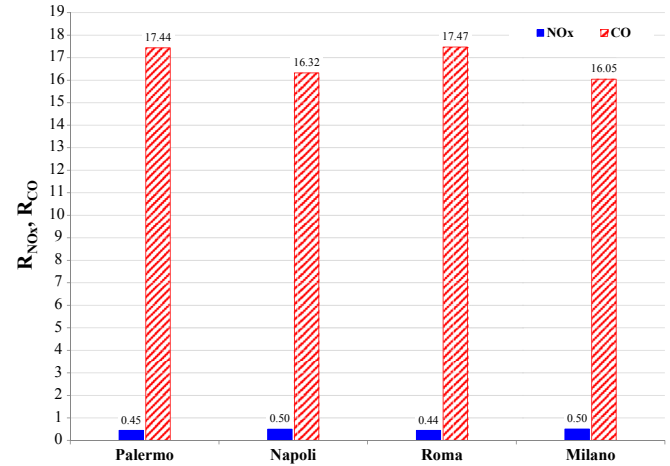


Fig. 11. R_{NO_x} and R_{CO} under electric load-following operation as a function of the city.

- ✓ whatever the city, the thermal load-following logic allows to obtain lower levels of CO with respect to the electric load-control strategy;
- ✓ whatever the MCHP control logic is, the influence of climatic conditions is quite relevant in terms of both NO_x and CO emissions:
 - a) under thermal load-following operation: the value of R_{NO_x} ranges from 0.59 when the building is located in Palermo up to 0.52 if Milano is the city under consideration; the value of R_{CO} is 7.37 when the building is located in Roma and 8.50 in the case of Milano;
 - b) under electric load-following logic: locating the building in Roma allows to achieve the minimum value of R_{NO_x} (0.44), while the maximum value (0.50) of R_{NO_x} is obtained when the building is located in Napoli or Milano; the values of R_{CO} range from 16.05 (Milano) up to 17.47 (Roma).

The results showed that, if compared to the conventional system assumed as reference, the proposed system is able to reduce the NO_x emissions, but it is characterized by larger CO emissions; therefore the simulation data highlighted that the MCHP unit is not completely suitable in reducing the local emissions.

However it can be noticed that, according to the experimental measurements, the CO emissions of the micro-cogeneration device decrease significantly with the electric load; therefore the thermal load-following control strategy should be considered instead of the electric-load following logic in order to mitigate the CO emissions associated to the proposed system. In addition it should be underlined that the MCHP unit analysed in this study is not equipped with the catalytic converter for abating the CO emissions because the model commercialized by the AISIN SEIKI company [17] within the non-European Union market was investigated; the model commercialized by the AISIN SEIKI company [17] for the European Union market is equipped with the catalytic converter and it is characterized by significantly lower emissions of CO. Therefore in the future the emissions of carbon monoxide associated to the device commercialized by the AISIN SEIKI company [17] for the European Union market should be also measured in detail and compared to the CO emissions associated to the conventional systems in order to obtain a comprehensive indication about the suitability of the MCHP device from the point of view of local emissions.

6. Conclusions

In this paper the NO_x and CO emissions of a residential building-integrated micro-cogeneration system were evaluated and compared with those of a conventional system composed of a natural gas-fired boiler (for thermal energy production) and a power plant mix connected to the central electric grid (for electricity production). A 6.0 kW_{el} reciprocating internal combustion engine fuelled with natural gas [17] was considered; its NO_x and CO emissions were derived from experimental measurements carried out by Lombardi et al. [20].

The analyses were carried out by using the whole building simulation software TRNSYS upon varying the city where the residential building is located as well as the MCHP control logic.

The simulation results showed that:

- in comparison to electric load-control strategy, thermal load-control strategy is characterized by lower CO emissions, but it is less favourable in terms of NO_x levels;
- whatever the city and MCHP control logic are, the proposed system allows for reducing the NO_x emissions in comparison to the conventional system, while the CO emissions associated to the conventional system are substantially negligible with respect to those of the proposed system;
- whatever the city, the reduction of the NO_x emissions is more pronounced in the case of electric load-following logic in comparison to the thermal load-control strategy;
- whatever the MCHP control logic is, the influence of climatic conditions is quite relevant in terms of both NO_x and CO emissions.

In the future the CO emissions associated to the device commercialized by the AISIN SEIKI company [17] for the European Union market (equipped with the catalytic converter) should be also evaluated and compared to the carbon monoxide emissions associated to the conventional systems based on separate energy production in order to get a final indication about the suitability of the MCHP device from the point of view of local emissions.

Of course the numerical results presented in the case study are representative of the specific situation, but, even if the specific results are not meant to be generalized, the synthetic and simple methodology followed in this study is highly suitable for running effective analyses with indicative or conventionally established emission data, regardless of the specific application. This aspect could be particularly useful to formulate emission policies for distributed energy systems.

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Nomenclature

Latin letters

A: area (m²)
c: specific heat (kJ/kg K)
e: emission (ppm)
E: energy (kWh)
h: heat transfer coefficient (W/m² K)
M: molar mass (kg/kmol)
m: mass (kg)
 $\dot{m}$: mass flow rate (kg/s)
P: power (kW)
s: thickness (m)
STS: simulation time step (s)
U: transmittance (W/m² K)
u: emission factor (g/kWh)

Greeks

α : air to fuel ratio (kg_{air}/kg_{fuel})
 η : efficiency (–)

λ : thermal conductivity (W/m K)
 ρ : density (kg/m³)

Acronyms

CO: carbon monoxide
FC: fuel cell
HDD: Heating Degree Days
ICE: reciprocating internal combustion engine
IF: flow inlet
IHE: internal heat exchanger
MCHP: micro-combined heat and power
MT: micro-turbine
OF: flow outlet
NO_x: nitrogen oxides
R: ratio between emissions of proposed system and conventional system
SE: reciprocating external combustion Stirling engine

Superscripts

B: boiler
CS: conventional system
E: energy
E_p: primary energy
E_{el}: electric energy
grid: related to the central electric grid
MCHP: micro-combined heat and power
SP: proposed system

Subscripts

air: air
CO: carbon monoxide
e: external
el: electric
exh: exhaust gases
frame: related to the frame of the window
fuel: natural gas
glazing: related to the glass of the window
i: internal
lim: limit value
NO_x: nitrogen oxides
p: primary
PP: power plant
th: thermal
window: related to the whole window
x: generic pollutant